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Fast gate turn-off in a merged thyristor-like structure

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Abstract

A concept of a merged thyristor-like structure which consists of two parts with different base gains is introduced. The high gain (HG) part serves as a source of an opening current for the low gain (LG) part and promotes it to the conducting open state so that the LG part becomes an additional channel for the total current flowing through the structure. During the turn-off process, the LG part serves as a source of the additional blocking current for the HG part, improving the turn-off characteristics of the merged structure. An analytical approach is developed to describe these inhomogeneous structures and their gate turn-off processes. The stationary distributions of the current density in the merged structures are calculated. The storage times and turn-off gains for homogeneous and merged structures are estimated. It is shown that the merged structures exhibit better turn-off characteristics in comparison with homogeneous structures. The direct two-dimensional simulations demonstrate faster turn-off in the merged structure and determine the regimes of operation where the effect can be reliably observed. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Low-power pnpn thyristor-like structures (TLSs) are used as light-emitting and lasing devices in optoelectronics. However, the problem of fast and efficient turn-off for such TLSs is still a challenge. Along with two-terminal light-emitting TLSs having a lot of applications as optoelectronic switches [1–3], several three-terminal thyristors are manufactured and described. The third terminal, the gate, is used in these TLSs for efficient turn-on and turn-off [4–12]. The signal applied to the gate terminals results in a transition between the high-conducting ON state and the low-conducting OFF state of the TLS. This transition may occur simultaneously in the entire structure. Meanwhile, if the width, i.e. the distance between the gate terminals is sufficiently large, an inhomogeneous intermediate state of incomplete gate turn-off (IGTO) can be established. This state is characterized by a squeezed current conducting channel in the center of the device (ON region) and a depleted OFF region near the gate terminals. The IGTO state is investigated both analytically [13–17] and numerically [18–22]. A stationary analytical solution is obtained in Refs. [23,24] for a low-power TLS with thin bases. This approach is further developed in Refs. [25,26] for the quasi-stationary propagation of a switching wave. It is shown that for a fairly small value of the gate current and low injection level in the bases, the velocity of the switching wave and, therefore, the turn-off time, is determined by the gate current and the current density in the ON region of the structure. The turn-off time is known [13] to consist of the storage time and the fall time. The former is a time interval it takes for the switching wave to propagate from the gate electrode to the device center and to set the reverse bias for the middle pn junction across its entire width. During the storage time, the total current through the structure remains approximately unchanged. The fall time is the time interval during which the depletion region of the middle pn junction expands in the floating base and the remaining carriers are removed from there by

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recombination. During the fall time, the total current decreases and the voltage across the structure rises rapidly. As a rule, the storage time is much greater than the fall time [13].

To decrease or even eliminate the storage time, one can choose narrow structures. Despite the fact that a narrow TLS has almost homogeneous turn-off which is faster than that with the switching wave being propagated in a wide TLS, the former can be turned off only by a very large gate current of the order of the total current through the structure. As a result, the turn-off gain, defined as the ratio of the total current to the gate current, would be small for narrow TLSs.

To increase the turn-off gain and decrease the turn-off time simultaneously, we introduce a merged TLS (Fig. 1(a)). The boundary conditions allow us to deal with only a half of the symmetrical device with two gate terminals. For simplicity, we consider only the left-hand side of the TLS with one gate electrode. The high gain (HG) part of the structure is in its ON state even at low anode current densities as its both base gains, $\alpha_{I,II}$, are sufficiently high, such that

$$\alpha_I + \alpha_{II} > 1. \tag{1}$$

The other low gain (LG) part has smaller base gains so that condition (1) is not met. For a structure with injection efficiency of emitters close to unity and homogeneously doped bases, $\alpha_{I,II} = (\cosh(\beta_{I,II} w_{I,II}))^{-1}$, where

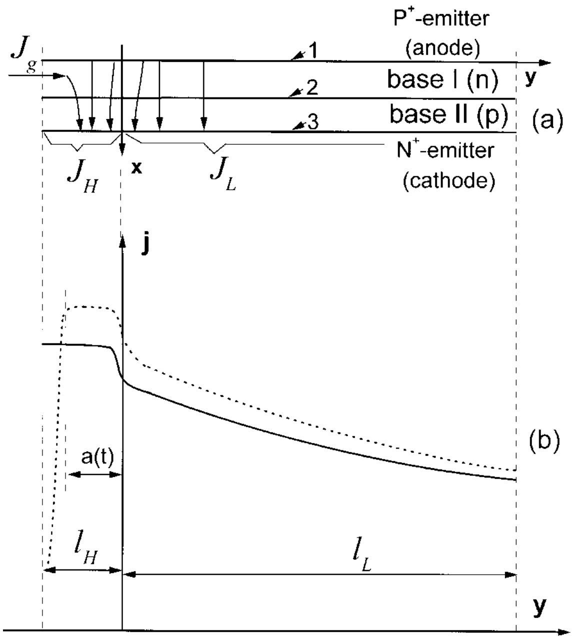

Fig. 1. (a) Merged HG/LG structure with gate current applied. (b) A sketch of the current density distribution in the merged HG/LG structure at zero (—) and nonzero blocking (- - -) gate currents.

$\beta_{I,II} = (D_{I,II}\tau_{I,II})^{-1/2}$ are the inverse diffusion lengths in both bases, $D_{I,II}$ and $\tau_{I,II}$ are diffusion coefficients and lifetimes of minority carriers in bases, respectively, and $w_{I,II}$ are the base lengths. In our consideration, the difference between the base gains in the LG and HG parts is caused only by smaller lifetimes in the LG part.

If isolated, the LG part would remain in the OFF state until the current density reaches a value that provides the necessary high injection level in the bases. The LG structure can be in its ON state at the low injection level, if the opening gate current is supplied. Merged to the LG part, the HG part serves as a source of the opening gate current. On the other hand, the same current can be considered as a "blocking gate current" for the HG part. Therefore, if this current is large enough to turn the LG part on, and is not large enough to turn the HG part off, the entire structure appears to be in its ON state. At the same time, if the sum of the base gains of LG part is only slightly less than unity, the current density in the merged HG part is only slightly higher than that in the LG part even for a structure where the LG part is substantially longer than the HG part.

Such a merged structure compared to a homogeneous HG structure of the same size would be turned off faster and with a smaller gate current. The reason is that actually we have to turn off only the HG part that is short and carries just a small portion of the total current. Once the HG part is turned off, the "opening" current to the LG part is no longer supplied, and it would be homogeneously turned off by itself for a time of the order of the recombination time in the LG part.

In this paper, the advantages of various merged structures are shown both analytically and numerically.

Here, we discuss the assumptions which are necessary for the analytical approach. The presented model is valid for controlled light-emitting and lasing thyristors with sufficiently small base lengths w_I and w_{II}. Then, we can assume that the voltage drops across the quasi-neutral regions of the bases are much smaller than those across the pn junctions, and introduce the electrical potentials of both bases. It is also assumed that the electrical potential varies much smoother along the structure (y direction, Fig. 1(a)) than across it (x direction). Therefore, the distribution of minority carriers in the bases can be considered as quasi-one-dimensional. We can represent it as a function of the x coordinate and electric potentials of both bases which are functions of the y coordinate. We also assume that the outer layers (anode and cathode) inject their majority carriers into the bases with the efficiency equal to unity.

We consider a structure with the longitudinal (in-plane) conductivity of the gated base, σ, being much greater than the conductivity of the floating base. This is fairly true for asymmetric structures where the gated base is doped much heavier than the ungated one. Low injection level and linear recombination rates are assumed in both bases. Detailed equations and solutions are to be found in Appendix A.

2. ON state of merged structures

Now we are interested in a merged structure whose current–voltage characteristics are close to that of a totally HG structure of the same size. This means that the HG part promotes the LG part to its ON state with the current density only slightly lower than that in the HG part. The mutual influence of the HG and LG parts depends on their parameters and widths. The closer the LG gains to the critical values (i.e. the closer $\alpha_{I_L} + \alpha_{II_L}$ to 1), the easier the LG part can be switched to the ON state. At the same time, the greater the width of the LG part, the weaker the influence of the HG part.

Fig. 2(a) illustrates these facts. The curves, calculated from Eqs. (A.5) and (A.6) of Appendix A, show that the total current through the structure versus the width of the LG part, l_L, while the width of the HG part, l_H, is fixed. l_L is normalized on l_H, and the current is normalized on the current through an isolated HG structure of the fixed width l_H at the same bias voltage. The dashed line serves as a guide line and represents an isolated HG structure. All the curves go farther from the dashed line as l_L grows. Curves 1–3 correspond to structures with different base gains. We have chosen $\alpha_{I_L} = \alpha_{I_H} = 0.7$ for all the three TLSs. Structures 1 and 3 have the same HG parts with $\alpha_{II_H} = 0.7$, but differ by the base gain of floating base in the LG part. For structure 1, $\alpha_{II_L} = 0.1$, which makes the sum of the base gains $\alpha_{I_L} + \alpha_{II_L} = 0.8$; $\alpha_{II_L} = 0.2$ for structure 3, so the sum of the LG part base gains is equal to 0.9, which is closer to unity, therefore curve 3 lies higher than curve 1. Compared to structure 1, structure 2 has the same LG part base gains, and a higher HG part base gain $\alpha_{II_H} = 0.8$. The higher the gain of the HG part, the stronger is its influence on the LG part, therefore curve 2 lies higher than curve 1.

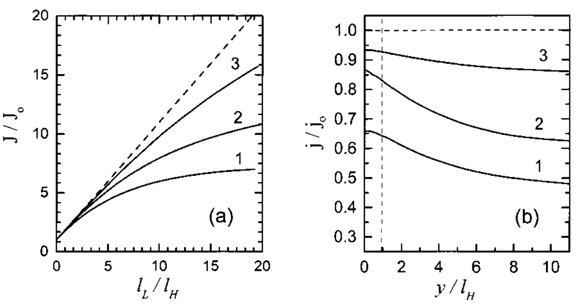

Fig. 2. (a) Current through the merged HG/LG structure at a fixed bias voltage versus the width of the LG part while the width of the HG part, l_H, is constant. J_0 is the current through the HG structure of the size of l_H. Curves 1–3 correspond to structures with different base factors, the dashed line corresponds to a totally HG structure. (b) The current density distributions for merged structures with $l_L = 10 l_H$ and base factors corresponding to structures 1–3 in part (a); j_0 is the current density in an isolated HG structure at the same bias voltage.

Fig. 2(b) depicts the current density distribution for structures 1–3 with $l_L = 10 l_H$. The current density is normalized on the current density in an isolated HG structure at the same bias voltage. It is seen that the current distribution is less corrupted in the structures with higher base gains in the LG part.

3. Storage time for merged structures

Now we discuss how fast the merged structures can be turned off. We have shown in Refs. [25,26] that the velocity of the switching wave is given by

$$v = \frac{J_g^2 - J_{g0}^2}{2 J_{g0} \tau j}, \tag{2}$$

where j is the current density in the ON region of the structure, J_g, the gate current and $J_{g0} = \sqrt{j I_1}$. I_1 and τ depend on the base widths and material parameters of the structure. The expression for I_1 is given in Appendix A. The analytical formula and calculations of τ can be found in Refs. [25,26] in the form $\tau = f_I \tau_I + f_{II} \tau_{II}$, where $f_{I,II}$ are functions of the base gains. Authors have obtained this result in Refs. [25,26] assuming that the ON region is half-infinite and j is constant during wave propagation. In the real situation, the size of the ON region, $2a(t)$, is finite, and the wave propagation does not change the value of the current flowing through the structure, $2J$, but squeezes or stretches the ON region. This means that j depends on time such that

$$J \approx a(t) j(t) = \text{const}. \tag{3}$$

If the velocity v is sufficiently small so that the process of wave propagation is quasi-stationary, we can use formula (2) with $j(t)$, $J_{g0}(t) = (I_1 J / a(t))^{1/2}$, and $v(t) = -\mathrm{d}a/\mathrm{d}t$.

Then, Eq. (2) can be rewritten as

$$v = -\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{J_g^2 - I_1 J / a}{2\tau J^{3/2} I_1^{1/2}} a^{3/2}, \tag{4}$$

and its solution for $J_g = const$ is

$$\frac{1}{\sqrt{a(t)} - \sqrt{a_g}} = \frac{e^{t/T}}{\sqrt{a(0)} - \sqrt{a_g}} + \frac{e^{t/T} - 1}{2\sqrt{a_g}}, \tag{5}$$

where $a_g = I_1 (J/J_g^2)$ is the "equilibrium" size of the squeezed ON region for given total and gate currents, and $T = 2\tau J / J_g$.

Now, we can obtain the turn-off characteristic time. The switching wave approach in a homogeneous structure is valid if the size of the ON region, $a(t)$, is greater than the size of a transition layer between the ON and the OFF regions that is estimated in Ref. [23] as

$$d \approx \left(\frac{I_2}{j}\right)^{1/2}, \quad \text{where}$$
$$I_2 = \frac{kT\sigma}{e}\frac{\alpha_{\rm I}(1-\alpha_{\rm II}^2)}{(\alpha_{\rm I}+\alpha_{\rm II}-1)(1-\alpha_{\rm II}+\alpha_{\rm I}\alpha_{\rm II})}.$$

After this point, the current density distribution changes strongly and can no longer be described as a switching wave between the two regions. We define here the storage time as an interval between the moment the gate current starts flowing and the moment the half-size of the ON region becomes equal to d. Actually, d depends on the current density in the ON region, so under the condition of a constant total current through the structure, the critical size of the ON region, which defines the turn-off time in the homogeneous structure, can be calculated as $d = I_2/J$.

First, we consider a homogeneous structure of size $2a_0$. As in Ref. [23], we can calculate the minimum value of the gate current that is capable of turning off the structure completely:

$$J_{\rm gc} = \sqrt{JI_1/d(J)} = vJ, \quad \text{where } v = \sqrt{I_1/I_2}.$$

Here, $J_{\rm gc}$ does not depend on a_0. The storage time of a homogeneous structure, $t_{\rm h}$, is calculated from Eq. (5) for $a(t_{\rm h}) = d$ as

$$t_{\rm h} = 2\tau\frac{J}{J_{\rm g}}\ln\left(\frac{(J_{\rm g}+vJ)(\sqrt{a_0/d}J_{\rm g}-vJ)}{(J_{\rm g}-vJ)(\sqrt{a_0/d}J_{\rm g}+vJ)}\right). \quad (6)$$

The dependence of $t_{\rm h}$ on a_0 is weak because $a_0 \gg d$ within the frameworks of our approximations. For large gate currents $J_{\rm g} \gg J_{\rm gc}$, Eq. (6) gives us

$$t_{\rm h} \approx 4\tau v\left(\frac{J}{J_{\rm g}}\right)^2.$$

The storage time is almost independent of the size of the structure and is determined only by the total currents J and $J_{\rm g}$.

Now, we consider the gate turn-off in a merged structure and show its superiority over the totally HG structure in terms of both turn-off time and gain. The first method to improve the turn-off in a HG structure of size a_0 is to merge an LG part to it. The current density distribution for a chosen size and parameters of the LG part can be calculated from Eqs. (A.5) and (A.6) or taken from Fig. 2. The total current can be represented as $J = j(a(t) + a_{\rm L})$, where $a_{\rm L}$ is an effective size of the LG part so that the current portion carried by the LG part, $J_{\rm L} = ja_{\rm L}$. It is shown in Appendix A (Eq. (A.9)) that in the properly designed merged structures, $a_{\rm L}$ can be assumed constant until $a(t)$ reaches the size of the transition layer, $d_{\min}$. This structure is properly designed if the current density in the LG part is almost evenly distributed and the LG part carries a significant portion of the total current. Only such structures would show great improvement of the turn-off in comparison with the conventional TLSs. Then, the solution of Eq. (2) is

$$\frac{1}{\sqrt{a(t)+a_{\rm L}}-\sqrt{a_{\rm g}}} = \frac{e^{t/T}}{\sqrt{a_0+a_{\rm L}}-\sqrt{a_{\rm g}}} + \frac{e^{t/T}-1}{2\sqrt{a_{\rm g}}}, \quad (7)$$

and the storage time $t_{\rm m}$ of the merged structure is calculated for $a(t_{\rm m}) = d_{\min} = p_1 d$, where $p_1 = 1 + (\sqrt{1+4a_{\rm L}/d}-1)/2$:

$$t_{\rm m} = 2\tau\frac{J}{J_{\rm g}}\ln\left(\frac{(J_{\rm g}+v_1J)(J_{\rm g}\sqrt{(a_{\rm L}+a_0)/d}-vJ)}{(J_{\rm g}-v_1J)(J_{\rm g}\sqrt{(a_{\rm L}+a_0)/d}+vJ)}\right), \quad (8)$$

where $v_1 = v(p_1 + a_{\rm L}/d(J))^{-1/2}$.

As $a_{\rm L} \to \infty$, formula (8) corresponds to Eq. (6). If $a_{\rm L} \gg d(J)$, it is convenient to rewrite Eq.(8) in the form

$$t_{\rm m} = 2\tau\frac{J}{J_{\rm g}}\ln\frac{(\sqrt{a_{\rm L}}+\sqrt{a_{\rm g}})}{(\sqrt{a_{\rm L}}-\sqrt{a_{\rm g}})}\frac{(\sqrt{a_0+a_{\rm L}}-\sqrt{a_{\rm g}})}{(\sqrt{a_0+a_{\rm L}}+\sqrt{a_{\rm g}})}. \quad (9)$$

Here, the complete gate turn-off is possible if $a_{\rm g} < a_{\rm L}$, thus the minimum value of the gate current is equal to $\sqrt{I_1J/a_{\rm L}}$ instead of $\sqrt{I_1J/d}$ for a homogeneous structure. An improvement in the turn-off gain may be estimated roughly by the factor $\sqrt{a_{\rm L}/d}$. More accurate calculations will be reported in Section 4. For $a_{\rm g} \gg a_{\rm L}$, the storage time is

$$t_{\rm m} \approx 4\tau v\left(\frac{J}{J_{\rm g}}\right)^2\frac{\sqrt{d}(\sqrt{a_0+a_{\rm L}}-\sqrt{a_{\rm L}})}{\sqrt{a_0(a_0+a_{\rm L})}}. \quad (10)$$

We obtain an essential decrease in storage time for $a_0, a_{\rm L} \gg d$ (Fig. 3). The ratio of the storage time in the

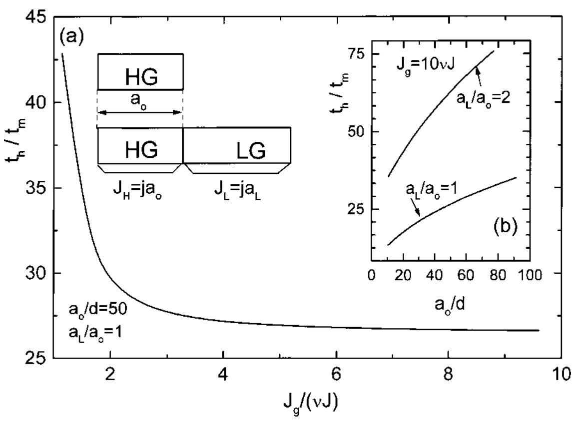

Fig. 3. The ratio of the storage time in the homogeneous structure, $t_{\rm h}$, to that in the merged structure, $t_{\rm m}$, designed by adding an LG part to the HG structure of size a_0, versus the gate current (a), and the size of the HG part (b).

homogeneous structure to that in the merged structure, t_h/t_m, drops steeply as the gate current increases. The value of t_h/t_m is almost proportional to a_L/a_0 (Fig. 3(a)), and is greater for longer devices (Fig. 3(b)). At the same total current J, the current density j in the initial homogeneous structure is higher than that in the merged structure, the ratio being equal to $(a_0+a_L)/a_0$ at the beginning of the turn-off process and to a_L/d at the end of the storage time. As the switching wave velocity depends on the deviation of the gate current from its equilibrium value, $J_{g0}=\sqrt{I_1 j}$, which is higher in the homogeneous structure, the same gate current makes the switching wave to propagate faster in a merged structure.

The second way to construct a merged device is to replace a part of the initial structure with an LG part while keeping the total length of the structure constant. Let the length of the remaining HG part be a_0/k, where $k>1$. We have to introduce parameter r which shows the difference between the current–voltage characteristics of the initial and the merged structures: at the same bias voltage with zero gate current, the total currents through the initial and the merged structure differ, $J_m = rJ_h$. The value of r can be calculated from Eqs. (A.5)–(A.8). In Fig. 2(a) curves for structures with greater r would be positioned higher. If r is close to unity, the current density in the HG part is slightly greater than that in the initial structure, so the switching wave moves a little bit slower, however it should propagate through the HG part only rather than through the entire device. Now, the storage time ends when the ON region of the HG part, $a(t)$, reaches the size of $d_{\min}=p_2 d$, where $p_2 = 1+((1+(4(r-1/k))(a_0/d))^{1/2}-1)/2$. The total current can be represented as $J = j(a(t)+a_0(r-1/k))$, where r remains constant for $a(t)>d_{\min}$. Then, the storage time is given by

$$t_m = 2\tau\frac{J}{J_g}\ln\left(\frac{(J_g+\nu_2 J)(J_g\sqrt{(ra_0)/d}-\nu J)}{(J_g-\nu_2 J)(J_g\sqrt{(ra_0)/d}+\nu J)}\right), \tag{11}$$

where $\nu_2 = \nu(p_2+(r-1/k)a_0/d(J))^{-1/2}$. The minimum gate current which results in $a(t)=p_2 d$ is now equal to $\nu_2 J$ compared to νJ in the homogeneous structures. For $J_g \gg \nu_2 J$, the storage time is

$$t_m \approx 4\tau\nu\left(\frac{J}{J_g}\right)^2\sqrt{\frac{d}{a_0}}\left(\frac{1}{\sqrt{p_2+(r-1/k)}}-\frac{\nu}{\sqrt{r}}\right). \tag{12}$$

Fig. 4 illustrates Eq. (11). The ratio t_m/t_h decreases rapidly as the gate current grows (Fig. 4(a)), it is almost proportional to parameter r (Fig. 4(b)). The storage time t_m decreases considerably, if the HG part is shortened up to several critical sizes (Fig. 4(c)). Formula (5) is no longer valid if $a(t)<p_2 d$, so we can plot t_m/t_h for limited values of k only. A further shortening of the HG part

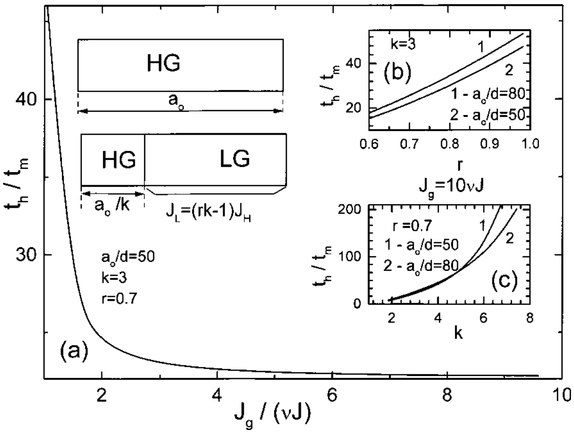

Fig. 4. The ratio of the storage time in the homogeneous structure, t_h, to that in the merged structure, t_m, designed by replacing a part of the initial structure with an LG part, versus the gate current (a), the parameter r of the LG part (b), and the width of the remaining HG part (c).

leads to a smaller total current at the same bias voltage, and may result in a transition of the structure to its OFF state even without a gate current.

4. Turn-off gain for merged structures

The following qualitative consideration shows why the merged structure has a high turn-off gain. Let the gate current $J_g^{\min}$ completely turn off an isolated HG structure of fixed length, l_H, and j is the current density in the structure at zero gate current: $jl_H = J_H$. Then, we consider a merged structure consisting of the same HG structure and an LG part, and adjust the basis so that the current density in the HG part near the gate terminal at zero gate current equals j. Then, the gate current even less than $J_g^{\min}$ is enough to turn the merged structure off, because the LG part serves as an additional source of the blocking current from the other side of the HG part. Meanwhile, the current carried by the merged structure is substantially higher (Fig. 2(a)), because the LG part being promoted to the ON state may carry a big portion of the total current: $J = J_H + J_L$. For thyristors with narrow bases, the turn-off gain is small, even close to 1, which is unacceptable in switching circuits. Therefore, a merged HG/LG structure that allows us to control a greater total current by a smaller gate current is a way to resolve this problem.

The turn-off gains for merged structures were estimated in Section 3. To make accurate calculations of the turn-off gain, it is necessary to define the minimum value of the gate current, $J_g^{\min}$, that completely turns off the

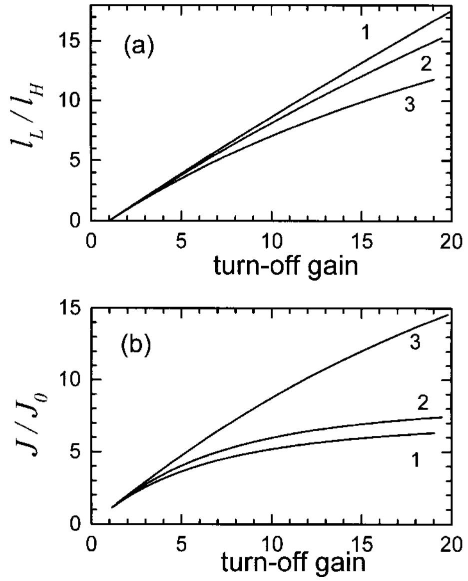

Fig. 5. The width of the LG part of the merged structure (a) and the current through the merged structure (b) as a function of the normalized turn-off gain. J_0 is the total current through an isolated HG structure of the size l_H.

structure. Actually, this value depends on the resistance R_a connected in series with the thyristor. To define J_g^{min} which would be independent of R_a, we can set a formal condition: the middle pn junction should become reverse biased completely at a constant total current (formally, $R_a = \infty$). We can use the analytical approach described in Appendix A (Eqs. (A.5) and (A.6)) to calculate the turn-off gain versus the length of the LG part. Curves 1–3 in Fig. 5 correspond to structures with the same parameters as those in Fig. 2. The gain is normalized on the turn-off gain of a fairly long isolated HG structure, whose current gain is independent of the length of the structure. Fig. 5 depicts the size of the LG part (a) and the total current through the structure (b) as a function of a turn-off gain. The size of the LG part, l_L, is normalized on the size of the HG part, l_H, which is fixed. The total current is normalized on the total current through an isolated HG structure of size l_H. Fig. 5(a) shows that merged structures with smaller base gains has a higher turn-off gain, although from Fig. 5(b) we can conclude that the current–voltage characteristics for such structures are more corrupted.

5. Simulation

Based on the analytical consideration, we have shown that if properly designed, a merged HG/LG structure has better turn-off gain and turn-off time. To confirm these results, we have performed direct two-dimensional numerical simulations of a model GaAs thyristor. This simulation is just an illustration of the new concept and the structure should not be considered a prototype of a real device that would have require a different design and additional optimization.

The simulation based on the isothermal drift diffusion model has been performed with the device simulator 'ATLAS' by Silvaco International [27]. The simulator solves self-consistently the Poisson equation and the continuity equations for electron and hole currents. The recombination terms in the continuity equations include optical ($B_0 = 3 \times 10^{-10}$ cm^3/s) and Shockley–Read–Hall (SRH) recombination. The values of SRH recombination lifetimes are $\tau_n = \tau_p = 10^{-9}$ s everywhere except the floating p-doped base of the LG part, where $\tau_n = \tau_p = 2 \times 10^{-10}$ s. Auger recombination is negligible at the given regimes of the device operation and was not taken into account. Constant low field mobilities and temperature 300 K are assumed.

The current–voltage characteristics of the thyristor structures at zero gate current are shown in Fig. 6(a). Curves 1 and 3 represent a totally HG and a totally LG structures, and curve 2 corresponds to the merged HG/LG structure. All the three structures are of the same length 110 μm, for the merged structure $l_H = 10$ μm and $l_L = 100$ μm. Structures differ only by their SRH recombination lifetimes in the floating base. This difference can be achieved by different dopants. Generally, the base gains can be reduced by higher doping concentrations which result in a stronger radiative recombination. The effect of turn-off improvement can be observed numerically over a wide range of the total current between the holding currents of the LG and the merged structures.

Fig. 6(b) demonstrates the turn-off gain advantage of the merged structure. The graph shows the results of stationary simulations: an increase in the voltage across the structure, ΔV_a, versus gate current. Curves 1–3 correspond to the 110 μm long HG structure, merged HG/

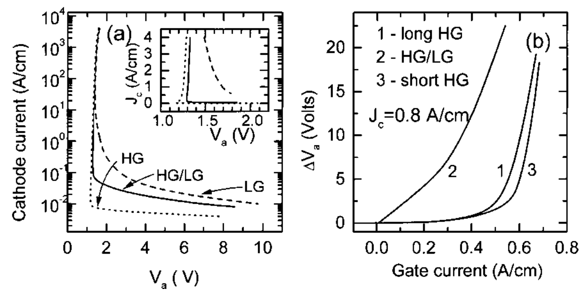

Fig. 6. (a) Calculated I–V characteristics of the merged (—), totally HG (· · ·), and totally LG (- - -) structures of the length of 110 μm. The inset shows the same characteristics in a linear scale. (b) Increase in the anode voltage versus the gate current at constant total current $J_c = 0.8$ A/cm.

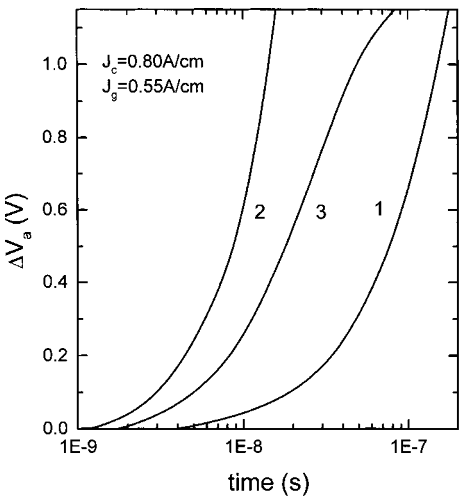

Fig. 7. The increase in the anode voltage ΔV_a as a function of time at $J_g = 0.55$ A/cm and $J_c = 0.8$ A/cm for structures 1 – long HG, 2 – merged HG/LG, and 3 – short HG.

LG structure described before, and short HG structure of 10 μm, respectively. Hereafter, we compare those three structures and refer to them as structures 1, 2, and 3. It is seen from Fig. 6(b) that the same increase in V_a requires a substantially smaller gate current in the merged structure than that in the entirely HG structure of any length.

Fig. 7 shows the results of transient simulations. ATLAS allows us to control either current through or electrical potential of each electrode, in the latter case, the control of resistance, capacitance and inductance being also an option. To avoid the result dependence on a specific value of R_a, we simulate the turn-off process with cathode current being held constant ($R_a = \infty$), $I_c = 0.8$ A/cm, and compute a voltage increment across the structure, ΔV_a. Let us assume, as in Section 4, that the structure is completely turned off if the middle pn junction is reverse biased in every point along the device. The DC simulation has shown that all the three structures 1–3 are completely turned off according to this definition if $\Delta V_a > 1.1$ V, so we can define the turn-off time as an interval between the moment the gate current starts flowing and the moment the voltage across the structure increases by 1.1 V. The turn-off here is initiated by a ramp of the blocking gate current with the ramp-time equal to 10^{-10} s. Fig. 7 depicts the transient process initiated in all the three structures by the same gate current. The merged structure turns off approximately 10 times faster than the long HG and five times faster than the short HG structures.

Another illustration of the idea can be found in Ref. [28], where the thyristor with attached LG part is connected into the real circuit. Decrease in the turn-off time is achieved because of not only a shorter storage time, but also a shorter fall time, which is partially defined by the recombination time in the LG part.

Therefore, the calculations illustrate better turn-off characteristics of the merged structures in comparison with conventional homogeneous devices even in the cases far beyond the assumptions made for analytical consideration.

6. Conclusion

We have proposed a new concept of merged TLSs that exhibit better turn-off characteristics in comparison with homogeneous devices and developed an analytical approach that allows us to describe the merged structure under low-injection-level conditions.

The first way to design a merged structure is to "attach" an LG part to the initial HG structure. This structure carries the same total current, and therefore has a smaller current density, which leads to a faster propagation of the switching wave even at smaller gate currents. As the switching wave propagates through the HG part only, the turn-off time of the total structure is considerably smaller, the effect being stronger for longer structures.

If the size of the device is not to be increased, the merged structure may be designed by replacing a part of the initial structure with an LG part. Here the turn-off characteristics are improved due to a shorter distance the switching wave should propagate.

To confirm the results of our analytical approach, we have performed direct two-dimensional numerical simulations. The simulations have shown that the advantages of the merged structures are observed numerically if the total current is greater than the holding current of the merged structure and smaller than that of the completely LG structure of the same length.

The presented analytical solutions together with numerical simulations can be used for optimization the composite structures for desired regimes of operation and turn-off characteristics.

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Appendix A

Based on the assumptions discussed in Section 1, we develop the analytical approach for a merged HG/LG structure. We consider low injection level and linear recombination rates R_p and R_n in both bases so that

$$R_p = p/\tau_I, \qquad R_n = n/\tau_{II}, \tag{A.1}$$

where p and n are the concentrations of excess minority carriers. For a conventional thyristor where the doping concentrations $N_{I,II}$ in the bases are constant, and

$$\frac{D_{II}\beta_{II}}{N_{II}\tanh(\beta_{II}w_{II})} \gg \frac{D_I\beta_I}{N_I\tanh(\beta_I w_I)},$$

we can obtain the equation for the electrical potential of the gated base (see Ref. [25] for details):

$$\frac{\partial}{\partial y}\sigma\frac{\partial\psi_I}{\partial y} = \frac{j_I}{(1-\alpha_{II})(1+e^{\psi-\psi_I})}\bigg[e^{\psi_I}(1-\alpha_{II}+\alpha_I\alpha_{II}) - e^{\psi}(\alpha_I+\alpha_{II}-1) - \frac{j_{II}}{j_I}e^{\psi-\psi_I}(1-\alpha_{II}^2)\bigg]. \tag{A.2}$$

Here, ψ, ψ_I are dimensionless (divided by kT/e) voltage drops across the structure and across the first pn junction, respectively, and

$$j_{I,II} = \frac{en_{I,II}D_{I,II}\beta_{I,II}}{\tanh(\beta_{I,II}w_{I,II})},$$

where $n_{I,II}$ are the equilibrium concentrations of minority carriers in the bases.

Deriving Eq. (A.2), we assumed that the first and the third pn junctions are forward biased and the voltage drops across them are much greater then kT/e. The last term in the square brackets appears due to taking into account the saturation current of the middle pn junction and was neglected in Ref. [25].

Eq. (A.2) can be used for both HG and LG structures. The HG structure is in the ON state (all the three pn junctions are forward biased) and can be turned off only by a blocking gate current. The LG structure is in the OFF state. As we have already mentioned, it can be turned on either by an opening gate signal or by a high anode current that ensures high injection level (the latter is not described by Eq.(2)).

For the HG structure being in the ON state without a gate current, the solution of Eq. (A.2) is:

$$e^{\psi_I(y)} = e^{\bar{\psi}_I} = e^{\psi}/A_H, \tag{A.3}$$

where

$$A_H = \frac{1-\alpha_{I_H}+\alpha_{I_H}\alpha_{II_H}}{\alpha_{I_H}+\alpha_{II_H}-1},$$

and $\alpha_{I,II_{H,L}}$ are the base gains defined in Section 1. Now, we introduce a new variable $\chi(y) = \psi_1(y) - \bar{\psi}_I$ in order to indicate deviation of the electrical potential from its value in an isolated HG structure. In Refs. [23,24], the same approach was used to describe the infinite HG structure with the gate current in the IGTO state. The gate current which ensures the stationary IGTO solution there is equal to $J_{g0} = \sqrt{I_1 j}$, where j is the current density in the ON region and

$$I_1 = \frac{2kT}{e}\sigma_H\frac{\alpha_{I_H}+\alpha_{II_H}-1}{1-\alpha_{II_H}}A_H\left[(1+A_H)\ln(1+A_H^{-1})-1\right].$$

We use the variable $\chi(y)$ in order to compare the solution for LG and merged structures with that for an isolated HG structure. Therefore, the solution even for an isolated LG structure without gate current, expressed in terms of $\chi(y)$, depends on the parameters of the HG structure:

$$e^{\chi(-\infty)} = \frac{A_H}{2A_L}\left(\sqrt{1+4\delta A_L}-1\right), \tag{A.4}$$

where

$$A_L = \frac{1-\alpha_{I_L}+\alpha_{I_L}\alpha_{II_L}}{1-\alpha_{I_L}-\alpha_{II_L}}, \qquad \delta = \frac{1-(\alpha_{II_L})^2}{(1-\alpha_{I_L}-\alpha_{II_L})e^{\psi}j_I/j_{II}}.$$

It can be shown that current density through the structure is proportional to e^{χ}: $j(y) = j_I e^{\bar{\psi}_I}e^{\chi(y)}$. As the voltage drop across the structure is much greater than kT/e, then $\psi \gg 1$, which makes $\delta \ll 1$. Then the current density in the LG structure is negligible in comparison with that in the HG structure.

Now, we consider a merged structure which consists of LG and HG parts. We integrate Eq. (A.2) for both LG and HG parts, taking into account the condition $d\chi/dy = 0$ on both sides of the structure. For the HG part we obtain:

$$\frac{d\chi}{dy} = R_H(e^{\chi_H}, e^{\chi}) = \left[\frac{2e}{kT}\frac{j_{I_H}}{\sigma_H}e^{\psi}\frac{\alpha_{I_H}+\alpha_{II_H}-1}{1-\alpha_{II_H}}\left\{(1+A_H)\times\ln\left|\frac{1+e^{\chi_H}/A_H}{1+e^{\chi}/A_H}\right| - e^{\chi_H}+e^{\chi}\right\}\right]^{1/2}. \tag{A.5}$$

Here, the boundary condition $d\chi/dy|_{y=-l_H} = 0$ corresponds to the zero gate current, and $\chi_H = \chi(-l_H)$ (see Fig. 1). For the LG part, we obtain

$$\frac{d\chi}{dy} = R_L(e^{\chi_L}, e^{\chi}) = \left[\frac{2e}{kT}\frac{j_{I_L}}{\sigma_L}e^{\psi}\frac{1-\alpha_{I_L}-\alpha_{II_L}}{1-\alpha_{II_L}}\left\{e^{\chi}\frac{A_H}{A_L}+(1-A_L+\delta)\times\ln\left|1+e^{\chi}\frac{A_H}{A_L}\right| - \delta\ln\left(e^{\chi}\frac{A_H}{A_L}\right)\right\}_{\chi_L}^{\chi}\right]^{1/2}. \tag{A.6}$$

Here, the condition $d\chi/dy|_{y=l_L} = 0$ corresponds to the center of the device, and $\chi_L = \chi(l_L)$. At the boundary between LG and HG parts, the continuity of the electrical potential which is proportional to χ and the total current in the gated base along y axis which is proportional to $\sigma d\chi/dy$ should be satisfied:

$$\sigma_H R_H(e^{\chi_H}, e^{\chi_B}) = \sigma_L R_L(e^{\chi_L}, e^{\chi_B}), \tag{A.7}$$

where χ_B is the value of χ at the boundary point: $\chi_B = \chi(0)$.

The distribution of the electrical potential and current density along the structure are the solutions of Eqs. ((A.5) and (A.6)). The widths of the HG and LG parts, $l_{H,L}$ that provide for chosen current densities at the HG and LG sides can be calculated as

$$\begin{aligned} l_H &= \int_{\chi_B}^{\chi_H} \frac{d\chi}{R_H(e^{\chi_H}, e^{\chi})}, \\ l_L &= \int_{\chi_L}^{\chi_B} \frac{d\chi}{R_L(e^{\chi_L}, e^{\chi})}, \end{aligned} \tag{A.8}$$

where χ_B is to be calculated from Eq. (A.7).

Solid line in Fig. 1(b) is a sketch of the current density distribution in a finite merged HG/LG structure without a gate current. If the gate current is supplied, we should integrate Eq. (A.2) with the boundary condition:

$$\sigma_H \frac{d\chi}{dy} = -\frac{e}{kT} J_g$$

on the gated side of the HG part of the structure. The corresponding distribution of the current density is sketched with the dashed line in Fig. 1(b). There is an ON region in the HG part where the current flows almost homogeneously, so we can introduce the size of this region, $a(t)$. The size d of the transition layer between the ON region and the OFF region near the gate electrode with almost zero current density is estimated in Ref. [23], d being determined by the parameters of the structure and the current density in the ON region. The size of the other transition layer between the HG and LG parts is of the order of d. Therefore, if $a(t) \gg d$, the current density in the ON region is almost evenly distributed, and the current carried by the HG part can be estimated as $J_H = ja(t)$.

The current distribution in the LG part which is determined by Eqs. (A.5) and (A.6) does depend on the current density in the ON region. In Section 4, we introduced the effective size of the LG part: $a_L j = J_L$, where J_L is the current carried by the LG part, which is proportional to $\int_0^{l_L} e^{\chi(y)} dy$. Let us estimate the change in the effective size of the LG part, a_L, if the current density is increased by a small value $\Delta j \ll j$. Then, using Eqs. (A.5)–(A.8), we can calculate the decrease of a_L:

$$\frac{\Delta a_L}{a_L} \approx \frac{\Delta j}{2j}\left(1 - \frac{j(l_L) l_L}{J_L}\right), \tag{A.9}$$

where $j(l_L)$ is the lowest current density in the LG part. Thus, generally, a_L decreases as j increases in the turn-off process. In Section 4, we consider only the structures where LG is promoted into the well-pronounced ON state with evenly distributed current density, so that $J_L - l_L j(l_L) \ll J_L$. Moreover, to exhibit much better turn-off characteristics, the current carried by the HG part, J_H should be noticeably smaller than J_L. This means that maximum change in the current density during the turn-off process is also small: $\Delta j/j = J_H/J_L$. As $\Delta a_L/a_L$ is a product of two small factors, we can neglect the change in the effective size of the LG part when calculating the storage time in the properly constructed merged structures.

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